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16. ABSTRACT

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DOSE-RESPONSE FUNCTIONS FOR EFFECTS OF ACIDIC PRECIPITATION ON VEGETATION

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INTRODUCTION

Contamination of the atmosphere by gaseous, liquid, and solid components generated by anthropogenic emissions has been known for more than a century (1). Some of these pollutants, namely ozone (O_3) and sulfur dioxide (SO_2), are known to affect the growth, development, and yield of crops. National Ambient Air Quality Standards in the U.S. (2) and Scientific Criteria on Environmental Quality in Canada (3) have been developed to protect human health and welfare from injury. Recently, the presence of sulfuric and nitric acids, as well as other substances in rain, has raised conjecture as to their effects on the growth of plants (4). Research has been directed towards quantification of the relationship between doses of acids in precipitation and plant response (dose-response relationships). Knowledge of these relationships provides an objective basis for economic assessment of crop losses and contributes to the development of control strategies for pollutant emissions from the combustion of fossil fuels. The purpose of this article is to describe some aspects of the phytotoxicity of acidic precipitation and to propose some improvements in experimental approaches in order to develop accurate dose-response functions.

DOSE-RESPONSE RELATIONSHIPS

Fundamental concepts of the relationship between toxic agents and organisms have been developed over more than a century of research (5), and these concepts provide useful criteria for evaluating the effects of acidic precipitation.

Basic Principles of Dose-Response Relationships

The response of a receptor to a toxic agent is determined initially by the nature and properties of the toxicant and the characteristics of the receptor. For toxicity to occur, the toxic agent must enter the receptor and move to the site(s) of action (6). In so doing, the toxic agent or its reaction products must overcome the capacity of the receptor to avoid, detoxify, or tolerate the toxicant (7). Pathways of internal movement of the toxic agent and the initial site(s) of action usually are unknown. Even though the specific injurious processes are not known, dose-response relationships are derived from experiments in which graded levels of toxic agent are administered to the receptor under defined conditions. With respect to the effects of acidic rain, two important problems are measure of dose and identification of temporal factors that affect plant response.

Measures of Dose

Surrogate measures of dose are used with environmental contaminants and many other toxic agents because the nature of the toxic agent and its rate of actual contact at specific sites of action within the receptor are unknown. Hence, external concentrations and rates of application of contaminants are used as measures of dose. For acidic rain, dose of acids in natural and simulated rain events is based either on concentrations or total deposition expressed on a weight or equivalents basis, integrated over different time intervals (individual events, seasons, or years), and expressed as a function either of land area (kg or equivalents of hydrogen ions per hectar) or volume (volume-weighted mean pH). The expression of dose exclusively as hydrogen ions may be inadequate because other components in rain, such as sulfate and nitrate, may produce important effects on vegetation. If the effects of components of rain are additive, then an arithmetic weighting based on the relative contribution of each component to the observed responses will provide an adequate representation of dose. A more complex measure of dose would have to be derived if the components of rain interact in producing their effects on vegetation. The possibility of interactive effects of components of rain on vegetation needs to be explored in greater detail.

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Temporal Factors of Rainfall that May Affect Plant Response

Many environmental factors alter plant response to toxic agents. The importance of duration and frequency of events for effects of acidic rain has been recognized (8,9); nevertheless, the significance of these temporal factors for determining plant response has not received sufficient emphasis in research. Comparison of results between experiments, laboratories, and species usually is based on pH values, total hydrogen ion deposition, or concentrations of components in simulated rain. However, the impact of individual rain events can be modified, during the interval between events, by recovery of plants from injury through processes of repair and compensatory growth. Alternatively, repeated exposure to acidic rain may have a cumulative effect that is more accurately represented when temporal factors as well as concentrations are reported. Therefore, these comparisons would be facilitated by additional description of rain events to include: 1) percent of time with rain, 2) average duration of wet period, 3) average duration of dry intervals between wet periods, and 4) total amount of rain (Table 1).

EXPERIMENTAL CONSIDERATIONS

Much emphasis in scientific research is placed on the selection of treatmets, conditions, target organisms, and the proper control. However, the concept of a control may be inappropriate in research on acidic rain where the objective is to determine dose-response relationships for two reasons. First, there is no agreement on the composition of "natural" or "clean" rain. A pH of 5.6 has been suggested as a reasonable value because rain at ambient pressure and temperature contains dilute carbonic acid. However, rainfall in remote locations frequently exhibits pH values different from 5.6 due to the natural emissions of gases and particulate matter from seawater, volcanoes, and decomposition of organic matter (10). Second, the comparison of treatments with control values may not be relevant to the objectives of this research. The critical issue is to predict the effects on crop growth with contamination at, above, and below current levels so that the benefits and costs of less and more polluted rain can be determined. Dose-response functions provide this capability when the appropriate range of treatments is used because interpolation between levels can be made. However, extrapolation to acidities above or below those used in the experiments is unreliable when simple response functions are used (11).

Determining the Response Surface

Currently, linear polynomial functions are used to describe dose-response relationships for effects of acidic rain. One theoretical example of a single-plan response curve (Figure 1, line C) can be described in general form by equation 1.

1) $Y=a_0+a_1x+a_2x^2+a_3x^3$

In this equation, Y= the measured response; x= treatment dose; a_0, a_1, a_2, and a_3 = parameters defining the function. Statistical procedures for constructing response curves from quantitative treatment levels have been published (12) and applications to air pollution studies have been described (13, 14). The magnitude of the values of the parameters have great biological and practical significance because they determine the exact shape of the dose-response functions. Thus, they provide the basis for comparisons of results between experiments and species. Climatic, edaphic, and cultural conditions affect the form of the functions, and the values of the parameters so the influence of these factors must be included in dose-response functions when they are significant. The presence of another air pollutant should be identified as an environmental factor that can alter the effects of acidic rain. Although a few experiments have been conducted with both acidic rain and SO_2 (15) or O_3 (16), the joint action of gaseous pollutants and acidic rain still is unclear. Complete integration of all factors that modify plant response to acidic precipitation may require the use of more advance methods for determining response surfaces (17).

TABLE 1. COMPARISON BETWEEN EXPERIMENTAL APPLICATIONS OF SIMULATED ACIDIC RAIN TO FIELD-GROWN CROPS AND ACTUAL PRECIPITATION IN THE EASTERN U.S.

Location or Crop	Percent of Time with Rain[1]	Avg. Duration of Wet Periods[1], hours	Avg. Duration of Dry Intervals, days	Mean Summer Rainfall, cm/week
Eastern U.S.[2]	3-5	2-3	1.4-5	0.8-1.2
Soybean (16)	1.5	1.0	2.8	3.2
Radish (20)	1.2	0.6	3.2	2.2
Bush Bean[3]	1.6	1.0	2.7	2.3

[1] Includes periods of intermittent rainfall

[2] Adapted from Tables 5 and 8 that summarize climatological data for: Connecticut, Illinois, Indiana, Kentucky, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Ohio, and Pennsylvania for the period of June through August, 1978 (32).

[3] Unpublished data.

Model Response Surfaces

It seems doubtful that a single type of dose-response function will describe all effects of acidic rain on all plant species because of the wide range of genetic material and modifying effects of edaphic and environmental factors (18). However, there are some hypothetical curves that serve as models for the response of vegetation (Figure 1, lines A-D). These models represent the principal questions to be resolved: 1) Do incremental increases in acidity produce concomittant decreases in crop yields (line A)? 2) Are there stimulatory effects over a wide range of acidities (line B)? 3) Are there stimulatory effects at low acidities and detrimental effects with higher acidities (line C)? 4) Is there a threshold value after which increases in acidity produce decreases in yield (line D)? Other model dose-response functions of more complex nature can be imagined, but it is obvious that each curve produces a different interpretation of effects of acidic rain. Some initial evidence for lines A-D have been provided by recent experimental results (18, 19, 20).

Range of Treatments

The range of concentrations for components of simulated rain is an important factor in the design of experiments to determine dose-response function. It seems reasonable to expect that variations in concentrations of inorganic components of rain might range several-fold between now and the end of this century. Even with reductions in emission controls or with great increases in controls, it is highly unlikely that concentrations of contaminants in rain could vary by as much as ten-fold during the next two decades. Therefore, a ten-fold range in concentration of hydrogen ions in simulated rain above and below current annual mean concentrations (pH 4.0 - 4.6 in eastern North America) provides a useful range of treatments. Sulfate and nitrate concentrations may change in a similar but not necessarily proportional way so a ten-fold range in their concentrations would also be an appropriate range. Increases in nitrate relative to sulfate may continue to occur as nitrogen oxide emissions increase more rapidly than sulfur oxides (1). In order to span differences over time and space, and represent changes within and between rain events, a reasonable range of sulfate to nitrate weight ratios in simulated rain is 0.4/1 to 4/1.

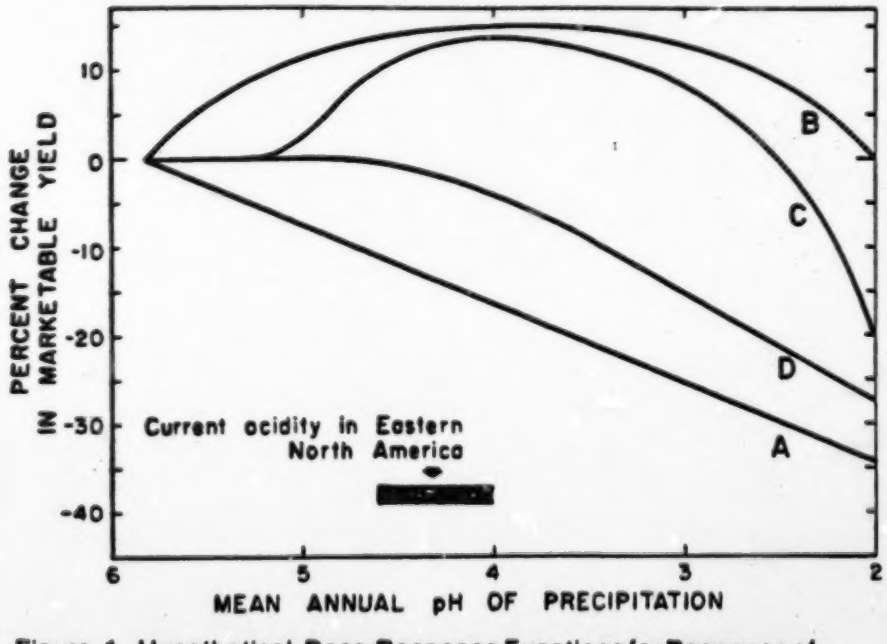

Figure 1. Hypothetical Dose-Response Functions for Response of Agricultural Crops to Changes in Acidity of Precipitation.

Field and Greenhouse Studies

The comparison of results from experiments conducted in greenhouses or growth chambers with results from field investigations also is a subject of concern. Field-grown plants seem to be less susceptible to development of foliar symptoms from application of simulated acidic rain than are plants grown indoors (20). Furthermore, greenhouse and field-grown plants may give different dose-response functions for yield. Field studies provide more realistic conditions for growth and exposure, but they have several disadvantages (21). One limitation is the occurrence of ambient rain and the extra supply of water deposited when simulated rain is applied. Changes in water supply can affect nutrient relationships and patterns of plant growth. Another disadvantage, in areas where ambient rain is acidic, is that results may be confounded by the extra supply of acids in ambient rain, which alters the expected volume-weighted mean hydrogen ion deposition for each treatment.

Improvements in Field Experiments

These considerations have led to the development of canopies for exclusion of ambient rain from field-grown crops. Canopies have been designed to cover the crop and exclude ambient precipitation and still allow for exposure to

normal environmental conditions. For example, in a recent test in Ithaca, NY, yield of bush beans was measured after exposure to simulated acidic rain applied with and without exclusion of ambient rain. Under the canopy, yield was increased with increased acidity of simulated rain, whereas yield was reduced when plants were exposed to both simulated and ambient acidic rain. The extra supply of water appeared to be a plausible explanation for the difference in yield because, at the lower pH values of simulated rain (pH 2.6 and 3.4), ambient rain contributed relatively little to total hydrogen ion deposition. Further comparisons need to be performed to verify that exclusion of ambient rain is necessary in experiments with simulated rain.

Another limitation to field experiments is the expense incurred in the construction of large exclusion devices and extensive systems for application of simulated rain. Experimental design may be constrained by space and equipment and it may not be possible to adequately replicate treatments in order to overcome variability between plots. Some alternative approaches have been used to improve the precision and accuracy of experiments. For example, analysis of soil characteristics in each plot provides data on inherent plot-to-plot variability that can be used in statistical analyses of data on growth and yield. In a recent test, we found that the sensitivity of an experiment to determine the effect of acidic rain on yield of bush bean was improved by including measures of soil fertility (N-P-K) as covariates.

A better method for the statistical control of plot-to-plot variability may be to obtain data on the growth and yield of plants located in untreated plots immediately adjacent to treated plots (22). We were able to improve the precision of an experiment to determine the effects of simulated acidic rain on field-grown spinach by using data on growth of plants in companion control plots. Further studies comparing the efficiency of each method need to be performed, but both techniques may be valuable tools in the design and analysis of field experiments.

INTERPRETATION OF RESULTS

We have assumed that the development of dose-response relationships, as previously described, is a critically important step in the effort to provide a scientific basis for strategies concerning the control of emissions of precursors of acidic rain. To date, dose-response experiments have emphasized effects of acidic rain on growth and yield of plants. Hypotheses can be developed from these empirical relationships to provide a basis for investigating the mechanisms of action of acidic rain.

Empirical Relationships

Line C in Figure 1 provides an example of a complex dose-response function that can be used to illustrate the development of explanations for the biological action of acids in rain. Four phases of this dose-response relationship can be identified. With low doses of acids in rain, there is no significant departure of yield from normal for a particular set of climatic and cultural conditions. With increasing dose (decreasing pH of rain), yield rises above normal due to a stimulatory effect of one or more components of rain, possibly nitrate and/or sulfate. In this case, the magnitude of the stimulation would be dependent on the extent to which these nutrients are limiting to the growth of the crop for the particular soil and rate of fertilizer addition. The stimulatory effect might, however, be due to hydrogen ions by analogy with the general principle of stimulation of biological systems by low concentrations of potentially toxic agents (23, 24). With higher doses of acidity (still lower pH values), a competition may ensue between stimulatory and inhibitory effects producing a leveling off in line C. At even higher acidities (below pH 2.5 in line C), the inhibitory effect of acidity predominates. For these proposed explanations to have predictive value for ambient situations, it is necessary to understand their physiological and biochemical basis.

Mechanism of Action

Referring only to hydrogen ions because they seem to be the most likely cause of toxicity, we can depict the relationships between internal and external sources of hydrogen ions as in Figure 2. The

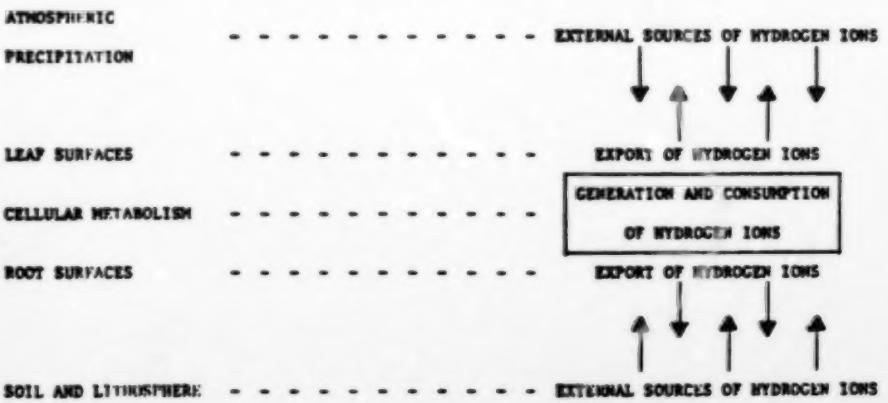

Figure 2. Biochemical Control of Acidity in Plant Tissues.

initial site of contact of acidic rain with vegetation is the surface of the leaf where absorption and removal of chemical species occurs (25, 26). However, the sites of action probably are within the leaf either on cell walls, cell membranes, and /or within the cytoplasm. Hydrogen ions are generated and consumed by metabolic reactions within plant cells. They also are transported across leaf and root surfaces. In the field, the acidity of rain may be neutrilized at the leaf surface by soil particles, particles deposited from the atmosphere, or by compounds secreted to the leaf surface (27). Once hydrogen ions have penetrated the leaf, the rate and degree of acidification may be determined by the buffering capacity of fluids within the leaf (28). Alternatively, they may contribute to net hydrogen ion flux and affect important metabolic reactions (29). A detailed mechanistic model based on physiological and biochemical explanations of dose-response relationships ultimately must be validated by testing predictions against reality in actual field situations.

CONCLUSIONS

In the eight-year period since the appearance of modern studies on effects of acidic precipitation on vegetation (30), considerable new information has been provided. However, there has been no direct demonstration of harmful effects to plants by ambient acidic rain in North America and there remains considerable uncertainty about the potential risk to cultivated and native plants (1, 4, 31). Current efforts to describe the relationships between dose of acidity and effects on plants require improvement in experimental approaches to provide results that are more relevant to actual field situations. Mechanistic models that describe the physiological and biochemical basis for effects of acidic rain on plants will be required to provide confidence in predictions of plant response to current and future levels of contaminants in precipitation.

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